

## The Next Milestone: A Multicarrier Acoustic MODEM with Channel- and Network-Adaptivity for Underwater Autonomous Distributed Systems

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### LONG-TERM GOALS

The long-term goal is to develop a practical multicarrier modem for underwater telemetry and distributed underwater sensor networks that can adapt to varying channel conditions and support advanced networking functionalities. This modem will be a major milestone on the path to a new era of underwater distributed networks.

### OBJECTIVES

We have three objectives in this project.

1. ***Make OFDM work underwater.*** The success of multicarrier modulation in the form of orthogonal-frequency-division-modulation (OFDM) in radio channels illuminates a clear path one could take towards high-rate underwater acoustic communications. However, earlier work on the application of OFDM in underwater has only had limited success. We aim to *make OFDM work* in underwater environments.
2. ***Channel- and network-aware modulation, coding, and scheduling.*** We aim to develop a layered coding structure with joint inter- and intra-packet coding. Intra-packet coding uses error-correction codes to deal with channel distortion and ambient noise, while inter-packet coding uses erasure-correction codes to cope with channel and network disruptions. This layered coding approach facilitates non-flow-based data delivery over single or multiple routing-paths, and can autonomously-adapt to channel and network conditions.
3. ***Prototype development.*** We aim to develop a stand-alone OFDM modem prototype that integrates the innovative algorithms developed in this project.

### APPROACH

We aim to make OFDM work in underwater and build a practical multicarrier modem prototype. We have proposed an effective method to mitigate the non-uniform Doppler effect of underwater channels,

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and published the first IEEE journal paper on underwater OFDM [Li et al'08]. We have also presented the first experimental result in the literature on underwater multi-input multi-output (MIMO) OFDM [Li et al'07]. As of now, the feasibility of OFDM for underwater acoustic communications is well accepted by the research community.

Over the past year, we have worked on the following aspects.

- 1) We continue to improve the receiver robustness through innovative algorithms and increase the data rate through the deployment of MIMO techniques.
- 2) We investigate the joint use of erasure- and error-correction coding to handle packet loss in unreliable networks.
- 3) We continue our prototype development using both floating- and fixed-point DSP platforms.

We collaborate with Mr. Lee Freitag and Dr. James Preisig from WHOI who have conducted various underwater experiments for our designed signals. We discuss with Dr. Milica Stojanovic from MIT/Northeastern to improve understanding on OFDM receivers. We work with Dr. Peter Willett from UConn on receiver algorithms, and Drs. Zhijie Shi and Jun-Hong Cui from UConn on modem prototype development.

## WORK COMPLETED

For the past year, we worked on extensive data sets recorded from three experiments.

- 1) RACE 08 experiment, Narragansett Bay, March 2008 (led by Dr. James Preisig)
- 2) GLINT08 test, Pianosa, Italy, July 2008 (through Mr. Lee Freitag)
- 3) SPACE08, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)

We have analyzed the data sets, and reported our results through various venues.

We have developed the modem prototypes using both the fixed- and floating-point DSP evaluation boards, for both single-transmitter OFDM and MIMO-OFDM.

We have involved undergraduate students into research through senior design projects:

- 1) Project: *Prototyping and Real Time Testing of Underwater Acoustic Modem*. Duration: Spring08-Fall08. Team: J. Thengumthiyil, Jason Thomas, Abbas Zaidi.
- 2) Project: *Localization for underwater sensor networks*. Duration: Fall08-Spring09. Team: Patrick Carroll, Ryan McDermott, Sherwayne Gordon, John Botticello

## RESULTS

**1) MIMO-OFDM for high data rate communication.** For the RACE08 experiment, we have reported MIMO-OFDM performance results of QPSK/8-QAM/16-QAM/64-QAM with two transmitters, QPSK/8-QAM/16-QAM with three transmitters, and QPSK/8-QAM with four transmitters where a

bandwidth of 4.8 kHz is used. The achieved spectral efficiencies are summarized in the following table.

$\alpha$  bits/s/Hz in RACE 08 experiment,  $B = 4.8$  kHz

	SIMO	2IMO	3IMO	4IMO
QPSK	0.58	1.17	1.76	2.35
8-QAM	0.88	1.76	2.64	3.52
16-QAM	1.17	2.35	3.52	-
64-QAM	1.76	3.52	-	-

In particular, a spectral efficiency of 3.5 bits/sec/Hz was approached with various configurations. In the VHF08 experiment, conducted at the Buzzards Bay, MA, April 2008, a data rate of 125.7 kb/s was achieved with two transmitters, 16-QAM modulation, rate 1/2 coding, and a bandwidth of 62.5 kHz. The performance results are summarized in the following table.

TABLE VII  
PERFORMANCE RESULTS FOR THE VHF08 EXPERIMENT. TWO TRANSMITTERS, RATE 1/2 CODING.

	Spectral efficiency	Data rate	Data Streams	Uncoded BER	Coded BER
$B = 31.25$ kHz, QPSK	1.0055 bits/s/Hz	31.4214 kb/s	Stream 1	0.0025	0
			Stream 2	0	0
$B = 31.25$ kHz, 8-QAM	1.5082 bits/s/Hz	47.1320 kb/s	Stream 1	0.0378	0
			Stream 2	0.0049	0
$B = 31.25$ kHz, 16-QAM	2.0010 bits/s/Hz	62.8438 kb/s	Stream 1	0.0868	0
			Stream 2	0.0319	0
$B = 62.5$ kHz, QPSK	1.0055 bits/s/Hz	62.8427 kb/s	Stream 1	0.0512	0
			Stream 2	0.0193	0
$B = 62.5$ kHz, 8-QAM	1.5082 bits/s/Hz	94.2640 kb/s	Stream 1	0.1102	0
			Stream 2	0.0488	0
$B = 62.5$ kHz, 16-QAM	2.0110 bits/s/Hz	125.6875 kb/s	Stream 1	0.1938	0
			Stream 2	0.1290	0

These results suggest that MIMO-OFDM is an appealing solution for very high data rate transmissions over underwater acoustic channels.

**2) Joint error- and erasure correction coding.** One major issue for underwater acoustic communication is that the link is unreliable but the channel feedback is too slow for requesting retransmissions. For such a scenario, we have proposed a layered coding approach that uses error-correction coding within each packet and erasure-correction coding across the packets. We have investigated how to optimally combine the strengths of error- and erasure-correction coding to optimize the system performance with a given resource constraint, or to maximize the resource utilization efficiency subject to a prescribed performance. For severe fading channels, such as Rayleigh fading channels, the tradeoff leans towards more redundancy on erasure-correction coding across packets, and less so on error-correction coding within each packet. For channels with better fading conditions, more redundancy can be spent on error-correction coding.

**3) Modem prototype development.** Last year, we reported an OFDM acoustic modem implementation using a floating-point TMS320C6713 DSP board. This year, we have further explored the

implementation issues. First, we optimized the floating-point implementation, which reduces the processing time per OFDM block from 1.7 s to 48 ms, **by about 35 times**. Second, we extended the implementation from a single input single output (SISO) system to a MIMO system, where two data streams were transmitted in parallel to double the transmission rate. Third, we implemented both SISO and MIMO modems using a fixed-point TMS320C6416 DSP board. Finally, we conducted extensive comparisons between the fixed- and floating-point implementations. The decoding time is summarized in the following table.

**Table 1: Processing time per block of 230ms**

	SISO OFDM	MIMO OFDM
Floating-point	47.96 ms	96.38 ms
Fixed-point	17.26 ms	36.55 ms

Hence, real time decoding is achieved with an impressive margin.

We compared the receiver performance using recorded data blocks from the experiment setup in a water tank as depicted in the last page of this report. For SISO OFDM, a 0.5 dB reduction on the noise tolerance is observed for the fixed-point implementation compared with the floating-point implementation, while the performance loss increases for MIMO OFDM, e.g., up to 2 dB at the block error rate of 0.01.

## IMPACT/APPLICATIONS

The success of our projects will have a deep impact. Providing high-data-rate and reliable multicarrier modems with networking functionalities, our projects will directly contribute to the development of distributed autonomous underwater networks that are of great interest to Navy, e.g., the AUV/UUV/glider networks.

## RELATED PROJECTS

I am the PI on the project “A Multicarrier Underwater Acoustic Modem with Precise-Ranging Capability,” 9/1/2007-8/31/2009, from National Science Foundation. This project is also related to OFDM modem development, but it has a different emphasis which is to provide the precise-ranging capability to the OFDM modem.

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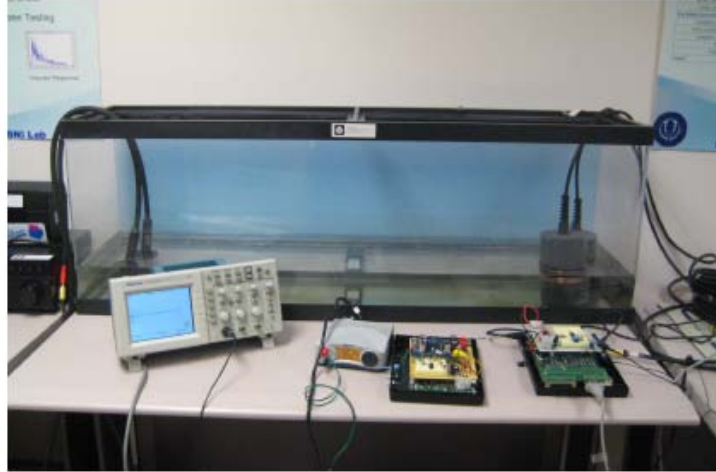
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## HONORS/AWARDS/PRIZES

Shengli Zhou received the 2007 Presidential Early Career Award for Scientists and Engineers (PECASE). He is the first faculty member from University of Connecticut to receive such a distinction. The award sponsor is Department of Defense (DoD).

Shengli Zhou received the UTC Professorship in Engineering Innovation, 2008-2011. The award sponsor is United Technologies Corporation (UTC).



*Figure 1. The experimental setup for modem development in the Lab led by S. Zhou.*



*Figure 2. The OFDM modem prototype accepts keyboard input and displays the received messages on a LCD panel.*